SEE Test Report:
Single event effects testing of the Microsemi APT50M38PLL Power MOSFET

Jean-Marie Lauenstein and Ray Ladbury, NASA/GSFC
Hak Kim, MEI Technologies

Test Date: 6 September 2008, 5 November 2008 Plan Date: 21 April 2008
Today's Date: 28 December 2008
Addendum added 16 July 2009

I. Introduction

This study was undertaken to determine the single event destructive (burnout and gate rupture) and transient susceptibility of the APT50M38PLL power MOSFET. The device was monitored for destructive events induced by exposing it to a heavy ion beam at the Texas A&M University Cyclotron Single Event Effects Test Facility. The primary failure mode for these devices was single-event gate rupture (SEGR), with a last pass/first fail drain-source voltage for the pristine devices of 225V/250V under 953 MeV Krypton irradiation and 150V/160V* under 1170 MeV Silver irradiation at zero gate-source voltage and normal beam incidence. Prior ^{60}Co γ-irradiation devices showed greater susceptibility to SEGR depending on the total dose.

II. Devices Tested

The sample size of the first testing was limited to 3 new devices and 3 devices having been previously exposed to ^{60}Co γ-irradiation. This limit was due to 3 additional new devices failing to meet vendor specifications during pre-exposure electrical characterization. Additional testing on 6 new devices was performed 2 months later to improve statistics and acquire angular (*i.e.*, not at worst case) data. All devices were manufactured by Microsemi Corp. and have a Lot Date Code of 0735.

The device is an 88 amp, 500 volt n-channel vertical power MOSFET, part of the Advanced Power Technology's MOS 7® family. The process features an aluminum metal gate structure in an interdigitated layout, and very low drain-source on-state resistance (0.042 ohms). Vendor electrical parameter specifications are given in Appendix A. The device is packaged in a metal P-Pack. The devices were delidded, visually inspected, and electrically characterized on-site by Hak Kim, MEI Technologies. The die measures 1.8 cm by 1.4 cm, giving a die area of 2.52 cm^2. The overlayer thickness for LET calculation is approximated to be up to 15 µm silicon-equivalent based upon information provided by Microsemi Corp.; the epilayer thickness is approximated to be 50 µm based upon current literature reports for 500 volt power MOSFETs. Upon query, Microsemi Corp. indicated that this device does not have a thick transitional layer separating the low-doped epitaxial layer and the substrate; therefore, ion ranges of 65 µm (Si) or greater (to the Bragg peak) should penetrate through the epilayer.

This testing was performed to evaluate these devices for use in a low-Earth orbit as power switches. Five devices per module will be used, with up to 5 modules used in the mission, making part-to-part variability more of a concern. This test report should be read with this factor in mind.

* The last pass/first fail drain-source voltage was decreased from 170V/180V to 150V/160V after additional pristine-device tests in March, 2009. These and other test results are presented as an addendum to this report.

III. Test Facility

Facility: Texas A&M University Cyclotron Single Event Effects Test Facility, 15 MeV/amu tune.
Flux: 5×10^3 particles/cm^2/s.
Fluence: 1×10^5 p/cm^2 or less if destructive events occurred sooner.

Ion	Incident LET (MeV•cm^2/mg)	Energy (MeV)	Range (µm in Si)
^{84}Kr	28.8	953	122
^{109}Ag	43.6	1170	107

IV. Test Setup

The test circuit, as shown in Figure 1, for the power MOSFET contains a Keithley 2400 source meter to provide the gate voltage (set to 0V or -5V during irradiation) while measuring the gate current. Gate current was limited to 1mA, and recorded via GPIB card to a desktop computer at 100 ms intervals. A filter was placed at the gate node of each DUT to dampen noise at the gate. An Agilent 6035A power supply provided the appropriate Vdd while monitoring the drain current (September tests), which was recorded via GPIB card at 100 ms intervals. A current probe at the source node of each DUT fed into a digital oscilloscope that was set to trigger on current transients of a predetermined size, saving them to file (September tests). Two DUTs were mounted on the test board, (Figure 3) each having a current probe at its source node. During the testing with Ag ions, the two current probes were placed on a single DUT to record current transients at both the source and drain to aid analysis of the failure modes. In preparation for ion exposure, each DUT in turn was placed 5 cm from the beam aperture, and centered within the 2-inch beam diameter. Ion exposures were conducted at normal angle incidence to 8 of the DUTs, and at either 45º tilt or roll for 4 DUTs.

During the November 5, 2008 testing, the test circuit was slightly modified (Figure 2). In lieu of current probes, a 1Ω, 50W resistor was placed at the source node, and two 1Ω, 50W resistors were placed in parallel at the drain node. Source and drain currents were then indirectly monitored using HP34401A digital multimeters placed across the resistors. No electronic load was used at the drain node.

The test setup was controlled via custom LabView codes written by Hak Kim for this test. One program controlled the power supplies, gate current limit, oscilloscope monitoring and transient capture, and gate, drain, and source current sampling and recording as appropriate for the different test setups. The second LabView code was designed to perform a parametric analysis before testing and after each run, recording Igs as a function of Vgs, gate threshold voltage, and drain-source breakdown voltage. These latter two measurements were critical due to the sensitivity of these devices to dose during heavy ion exposure.

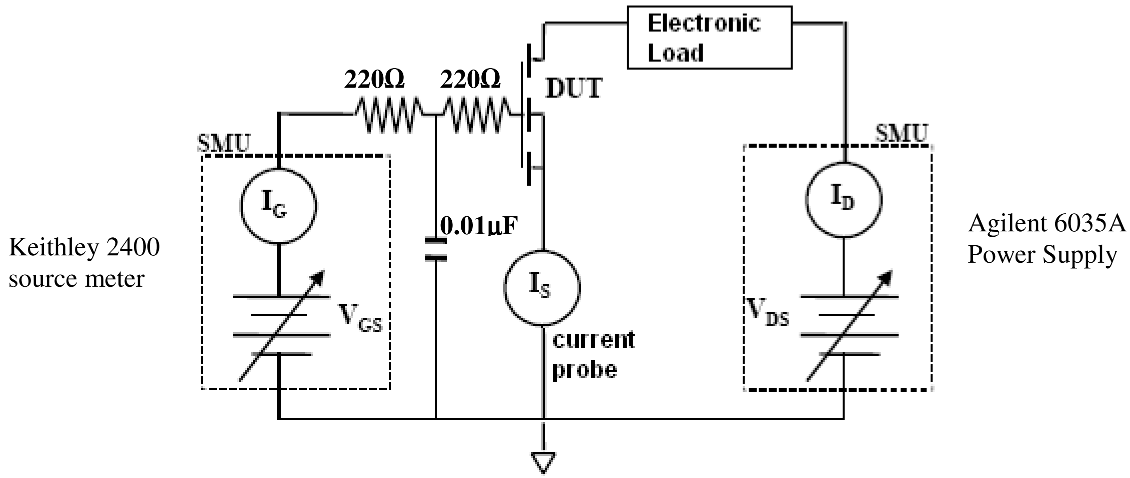


Figure 1. September 6, 2008 test setup for the APT50M38PLL power MOSFET.

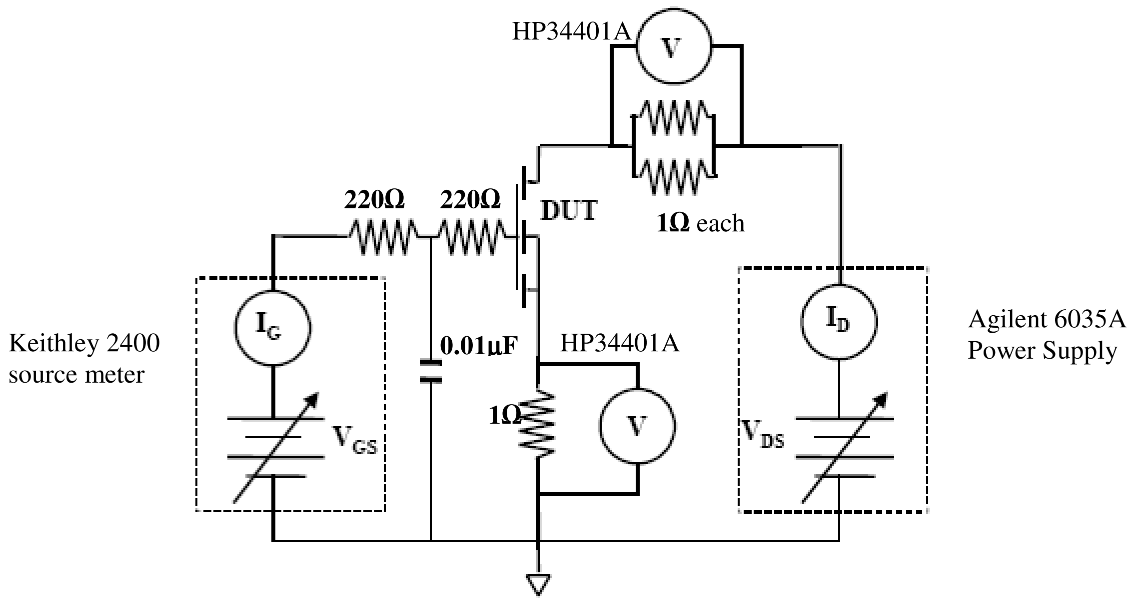


Figure 2. November 5, 2008 test setup for the APT50M38PLL power MOSFET.

Test Equipment:

a. Keithley 2400 source meter
b. Agilent 6035A System Power Supply (ECN 2114860)
c. Tektronix TDS784C Digital Scope (ECN 1953620)
d. Tektronix TCPA30C Amplifier (SN B020626) with TCP 312 probe
e. Tektronix TCP 202 probe
f. HP34401A Digital Multimeters
g. Lenovo ThinkCentre Desktop PC (ECN 3078134)
h. Armel PLW12K-400-400E Electronic Load (ECN 3080141)

Figure 3. Test equipment setup (6 September 2008) at TAMU for the APT50M38PLL power MOSFET. Left photo: control room. Right photo: beam cave. In right photo, two DUTs can be seen mounted on the testboard.

V. Test Results

Tests were performed at Texas A&M University Cyclotron Single Event Effects Test Facility on September 6, 2008 and on November 5, 2008. Two different monoenergetic ion beams (953 MeV krypton and 1170 MeV silver) were used. Data results suggest the primary failure mode of these devices is SEGR; however, 1 DUT experienced single-event burnout (SEB) when irradiated at 45º tilt, such that the ion trajectory was along the direction of the gate interdigitation. Complete test data and conditions are provided in Appendix B (6 September 2008) and Appendix C (5 November 2008). Appendix D contains a few examples of the strip tape and/or current probe data.[*]

A. Pristine Device Testing: Normal Beam Incidence

Two new devices were tested with 953 MeV krypton. Both experienced destructive failure at a drain-source voltage (Vds) of 250 volts when the gate-source voltage (Vgs) was held at 0 volts; the last passing Vds for these two devices was 225 volts. Substantial degradation of the gate threshold voltage (Vth) was seen following each exposure: the first device Vth degraded 0.94 V after 255 rad (Si) heavy ion cumulative dose; the second device Vth showed a 0.69 V degradation after only 93 rad (Si) heavy ion cumulative dose. Because of this precipitous degradation, the number of runs per device, hence the minimum Vds step size, had to be limited.

Initial testing with 1170 MeV silver was completed on only 1 new device as the remaining 3 DUTs failed on-site electrical characterization testing. Testing at a Vgs of 0 volts was therefore not performed to device failure; upon the device passing at 175 Vds, the gate voltage was decreased to –5 volts to test the impact of a slightly negative Vgs. At –5 Vgs, destructive failure occurred at a Vds of 180V, with a last-pass Vds of 150V. Again, precipitous degradation of Vth was seen during these runs, with the device Vth falling below vendor specification after less than 139 rad (Si). Additional testing was performed two months later: 2 new DUTs were again irradiated with 1170 MeV Silver at normal incidence, and both failed at 180 Vds under 0Vgs. The first device had a last-passing Vds of 170V; notably, its gate Vth fell below vendor specification after the first beam run, a dose of only 66.3 rad (Si). The second device was therefore only tested at 180 Vds in order to examine whether dosing from prior runs influenced the failure threshold.[*]

---

[*] Please see Addendum added July 16, 2009 for additional normal-incidence test results for this part.

B. Pristine Device Testing: Angular Beam Incidence

Angular testing at 45º tilt or roll was conducted with the 1170 MeV Ag beam. 45º tilt and 0º roll was defined as the angle orienting the beam line slightly down the interdigitation. 45º roll/0º tilt therefore oriented the beam slightly across the interdigitation. Two new devices were tested at each orientation; all 4 DUTs had a last passing Vds/first failing Vds of 290V/310V at 0 Vgs. One DUT in the 45º tilt orientation experienced SEB; the other 3 DUTs failed from SEGR.

C. Dosed Device Testing: Normal Beam Incidence

Prior ^{60}Co gamma-irradiation total ionizing dose preliminary testing suggests that these parts cannot withstand more than 1 krad (Si) mission dose in order to maintain a viable gate threshold voltage; unshielded mission dose is expected to be 12 krad (Si). We therefore explored with 1170 MeV Silver the interaction of prior total ionizing dose from gamma-irradiation and single-event destructive failure. The device previously dosed to 1 krad (Si) experienced destructive failure at 0 Vgs and 180 Vds, similar to the pristine devices. Two devices previously dosed to 4 krad (Si) and subsequently annealed at room temperature for one week both failed at a Vds of only 150 volts with 0 Vgs. These results suggest that the threshold for single-event device failure is reduced by prior cumulative total ionizing dose from gamma irradiation.

VI. Conclusions

Based upon the test results, the APT50M38PLL power MOSFET does not pass single-event effect qualification for the project. The Silver irradiation test findings indicate that these devices are a risk for single-event destructive failure at the application drain bias range of 126-165 volts; this risk substantially increases with dose. These devices are a category 4 risk, and cannot be used for space-based missions. The devices parametrically degrade and fall out of vendor specification rapidly with less than a few hundred rads (Si) of dose from heavy ion irradiation. The expected mission dose for these parts will be proton-dominated. The parametric degradation by heavy ion exposure seen in these tests suggests that gamma-irradiation underpredicts on-orbit degradation for a given total dose. The mechanisms for the greater degradation in power MOSFETs from proton and heavy ion irradiation are not yet understood, and have only recently been reported in the literature[1].

---

[1] J.A. Felix, M.R. Shaneyfelt, J.R. Schwank, S.M. Dalton, P.E. Dodd, and J.B. Witcher, "Enhanced Degradation in Power MOSFET Devices Due to Heavy Ion Irradiation," *IEEE Trans. Nucl. Sci.*, vol. 54, no. 6, pp. 2181-2189, Dec. 2007.

L.Z. Scheick and L.E. Selva, "Effect of Dose History on SEGR Properties of Power MOSFETs," *IEEE Trans. Nucl. Sci.*, vol. 54, no. 6, pp. 2568-2575, Dec. 2007.

Appendix A

TABLE A1. APT50M38PLL Vendor-specified Electrical Parameters.

Parameter	Condition	MIN	MAX	Units
Gate Threshold Voltage (VGSth)	Vds = Vgs, Id = 5 mA	3	5	V
Zero Gate Voltage Drain Current (Idss)	Vds = 500V, Vgs = 0V		100	uA
Drain-Source Breakdown Voltage (BVdss)	Vgs = 0V, Id = 250uA	500		V
Gate-Source Leakage Current	Vgs = +/- 30V, Vds = 0V		+/- 100	nA
Drain-Source On-State Resistance	Vgs = 10V, Id = 44A (pulse test)		0.042	Ohms
Source-Drain Diode Forward Voltage	Vgs = 0V, Is = -88A (pulse test)		1.3	V
Turn-on Delay Time (td(on)) *	*Vgs = 15V, Vdd = 250V, Id = 88A, Rg = 0.6ohms*	TYP = 17		ns
Rise Time (tr) *	*Vgs = 15V, Vdd = 250V, Id = 88A, Rg = 0.6ohms*	TYP = 22		ns
Turn-off Delay Time (td(off)) *	*Vgs = 15V, Vdd = 250V, Id = 88A, Rg = 0.6ohms*	TYP = 50		ns
Fall Time (tf) *	*Vgs = 15V, Vdd = 250V, Id = 88A, Rg = 0.6ohms*	TYP = 4		ns

Appendix B

Notes:

1. Data were taken at normal beam incidence on 6 September 2008.
2. Fluence indicated for runs resulting in device failure is at the time of beam shuttering but not necessarily when the failure occurred.
3. Maximum measurable BVdss is 511V due to equipment limitation.

Table B1. Pretest Characterization of DUTs.

Part SN	Vth	BVdss*	Igss +/-	Prior γ dose
	(Volts)	*(Volts)*	*(nA)*	*(krad (Si))*
209	3.94	511	30.7/30.7	n/a
150	3.75	511	39.1/49.7	n/a
15	3.77	511	22.8/29.5	n/a
186	2.97	511	42.5/43.5	1.05
211	1.78	417	57.5/33.3	4.00
208	1.75	329	37.4/39.0	4.00

*BVdss according to vendor-specified test condition (Vds at which Ids = 250uA, at 0Vgs.)

Table B2. Test data from 6 September 2008. Beam diameter = 2 inches; 5cm airgap. Runs 17-24 compose γ-dosed DUT tests.

Time	Run	S/N	Ion	Angle	LET	Energy	Range	Ave. Flux	Fluence	Dose	Cum.	VGS	VDS	Vth	Pass/	comments
	#			deg	MeV.cm2/mg	MeV	μm	#/cm2/s	#/cm2	rad (Si)	Dose	V	V	V	Fail	
12:00	1	209	Kr	0	28.8	953	122	2.13E+03	5.45E+04	25.16	25.16					not electrically contacting DUT
	2	209	Kr	0	28.8	953	122	2.13E+03	9.94E+04	46.63	71.79	0	125			
	3	209	Kr	0	28.8	953	122	2.18E+03	9.95E+04	45.92	117.7	0	150			
	4	209	Kr	0	28.8	953	122	2.17E+03	1.01E+05	46.4	164.1	0	175			
	5	209	Kr	0	28.8	953	122	2.41E+03	9.93E+04	45.8	209.9	0	200	3.06		
	6	209	Kr	0	28.8	953	122	5.99E+03	9.81E+04	45.24	255.2	0	225	3.00		
12:37	7	209	Kr	0	28.8	953	122	6.33E+03	6.72E+04	30.99	286.1	0	250		F: SEGR	
	8	150	Kr	0	28.8	953	122	5.89E+03	9.94E+04	45.86	45.86	0	200	3.32		
13:07	9	150	Kr	0	28.8	953	122	6.20E+03	1.03E+05	47.31	93.17	0	225	3.06		
13:15	10	150	Kr	0	28.8	953	122	6.39E+03	5.38E+04	24.8	118	0	250		F: SEGR	
	11	15	Ag	0	43.6	1170	107.2	5.75E+03	9.76E+04	68.09	68.09	0	125			
	12	15	Ag	0	43.6	1170	107.2	6.07E+03	1.01E+05	70.59	138.7	0	150	2.53		
15:20	13	15	Ag	0	43.6	1170	107.2	5.73E+03	1.02E+05	71.19	209.9	0	175	2.37		
	14	15	Ag	0	43.6	1170	107.2	6.05E+03	1.03E+05	71.75	281.6	-5	125	2.13		
	15	15	Ag	0	43.6	1170	107.2	5.92E+03	9.69E+04	67.65	349.3	-5	150	1.95		
	16	15	Ag	0	43.6	1170	107.2	5.61E+03	1.01E+05	70.74	420	-5	180		F: SEGR	
16:25	17	186	Ag	0	43.6	1170	107.2	4.55E+03	1.02E+05	71.2	71.2	0	125	2.51		(1050 rad (Si) gamma-dosed DUT)
16:40	18	186	Ag	0	43.6	1170	107.2	4.43E+03	9.98E+04	69.62	140.8	0	150	2.20		
	19	186	Ag	0	43.6	1170	107.2	4.57E+03	9.78E+04	68.26	209.1	0	180		F: SEGR	Broke on stress test
17:39	20	211	Ag	0	43.6	1170	107.2	3.73E+03	9.86E+04	68.78	68.78	0	125	1.69		(4 krad (Si) gamma-dosed DUT)
	21	211	Ag	0	43.6	1170	107.2	3.16E+03	9.98E+04	69.65	138.4	0	150		F: SEGR	Broke on stress test
18:17	22	208	Ag	0	43.6	1170	107.2	5.87E+03	9.84E+04	68.69	68.69	0	125	1.69		(4 krad (Si) gamma-dosed DUT)
	23	208	Ag	0	43.6	1170	107.2	5.73E+03	7.77E+04	54.22	122.9	0	150		F: SEGR	

Appendix C

Notes:

1. Data were taken on 5 November 2008. All DUTs were pristine.
2. Fluence indicated for runs resulting in device failure is at the time of beam shuttering but not necessarily when the failure occurred.
3. Maximum measurable BVdss is 510-511V due to equipment limitation.

Table C1: Pretest Characterization of DUTs

Part SN	Vth (Volts)	BVdss (Volts)	Idss (uA)	Igss +/- (nA)
40	3.71	511	0.575	47.5/35.3
31	3.69	511	0.982	26.1/43.6
16	3.76	510	1.1	22.9/29.3
22	3.93	511	1.41	14.0/75.2
45	3.71	510	1.1	46.4/22.0
35	3.81	511	0.587	47.0/17.9
202	3.79	510	0.898	59.3/16.6
37	3.65	511	0.479	11.3/25.3
4	3.68	510	2.02	7.4/32.2
11	3.86	510	0.862	19.2/33.5

Table C2: Test data from 5 November 2008. Beam diameter = 2 inches; 5cm airgap.

time	Run	S/N	Ion	Tilt	Roll	LET/ eff LET	Energy	Range/ eff	Ave. Flux	eff Fluence	Dose	Cum.	VGS	VDS	Vth	BVdss	Idss	Pass/	comments
	#			deg	deg	MeV.cm2/mg	MeV	µm	#/cm2/sec	#/cm2	rad (Si)	Dose	V	V	V	V	A	Fail	
18:00	1	40	Kr	0	0	28.8	953	122	1.35E+03	1.01E+05	4.40E+01	4.40E+01	-65	0					
18:14	2	40	Kr	0	0	28.8	953	122	1.17E+03	1.00E+05	4.38E+01	8.78E+01	-75	0	0.6	1	1.98E-01		Part looks dosed: stop
18:40	3	31	Kr	0	0	28.8	953	122	1.13E+03	9.97E+04	4.36E+01	4.36E+01	-80	0	0.6	0	1.94E-01		Dosed on the first run:stop
	4	16	Kr	0	0	28.8	953	122	1.30E+03	9.98E+04	4.37E+01	4.37E+01	-80	0	0.69	0	1.43E-01		dosed again
19:55	5	22	Kr	45	0	28.8/40.7	953	122/86.3	1.07E+03	1.00E+05	6.19E+01	6.19E+01	0	250	3.56	510	1.99E-06		
20:05	6	22	Kr	45	0	28.8/40.7	953	122/86.3	1.02E+03	9.98E+04	6.18E+01	1.24E+02	0	270	3.32	511	1.94E-06		
20:15	7	22	Kr	45	0	28.8/40.7	953	122/86.3	9.95E+02	9.97E+04	6.18E+01	1.85E+02	0	290	3.19	510	2.28E-06		
20:25	8	22	Kr	45	0	28.8/40.7	953	122/86.3	9.11E+02	8.16E+03	5.05E+00	1.90E+02	0	310				F: SEB	
20:45	9	45	Kr	45	0	28.8/40.7	953	122/86.3	1.04E+03	1.00E+05	6.20E+01	6.20E+01	0	290	3.21	510	1.65E-06		
20:54	10	45	Kr	45	0	28.8/40.7	953	122/86.3	9.10E+02	9.97E+04	6.17E+01	1.24E+02	0	310				F: SEGR	failed on gate stress test
21:20	11	35	Kr	0	45	28.8/40.7	953	122/86.3	6.80E+02	1.00E+05	6.20E+01	6.20E+01	0	250	2.49	511	6.02E-05		currents increased.
21:30	12	35	Kr	0	45	28.8/40.7	953	122/86.3	7.00E+02	1.00E+05	6.21E+01	1.24E+02	0	270	2.15	511	1.28E-04		Id, Is crept up - effect of Vth
21:43	13	35	Kr	0	45	28.8/40.7	953	122/86.3	6.45E+02	1.00E+05	6.19E+01	1.86E+02	0	290	1.95	511	2.23E-04		
21:54	14	35	Kr	0	45	28.8/40.7	953	122/86.3	6.56E+02	9.98E+04	6.18E+01	2.48E+02	0	310				F: SEGR	failed on stress test
22:10	15	202	Kr	0	45	28.8/40.7	953	122/86.3	6.23E+02	2.43E+04	1.50E+01	1.50E+01	?	?	3.78	510	4.67E-07		abort
22:21	16	202	Kr	0	45	28.8/40.7	953	122/86.3	6.04E+02	1.00E+05	6.20E+01	7.71E+01	0	290	2.62	511	2.24E-05		
22:22	17	202	Kr	0	45	28.8/40.7	953	122/86.3	5.82E+02	1.00E+05	6.19E+01	1.39E+02	0	310				F: SEGR	failed on stress test
23:13	18	37	Ag	0	0	43.6	1170	107.2	1.02E+03	1.00E+05	6.63E+01	6.63E+01	0	160	2.56	511	1.18E-05		
23:24	19	37	Ag	0	0	43.6	1170	107.2	7.99E+02	9.98E+04	6.62E+01	1.33E+02	0	170	2.27	511	2.53E-05		
23:34	20	37	Ag	0	0	43.6	1170	107.2	7.48E+02	9.97E+04	6.61E+01	1.99E+02	0	180				F: SEGR	part failed stress test
23:44	21	4	Ag	45	0	43.6/61.6	1170	107.2/75.8	8.75E+02	9.99E+04	9.37E+01	9.37E+01	0	170	2.82	510	2.67E-06		(accidentally at 45deg)
0:04	22	4	Ag	45	0	43.6/61.6	1170	107.2/75.8	8.24E+02	9.99E+04	9.37E+01	1.87E+02	0	180	2.56	511	4.23E-06		
0:14	23	4	Ag	45	0	43.6/61.6	1170	107.2/75.8	7.77E+02	9.98E+04	9.36E+01	2.81E+02	0	190	2.43	510	6.09E-06		
0:25	24	4	Ag	45	0	43.6/61.6	1170	107.2/75.8	7.53E+02	9.99E+04	9.37E+01	3.75E+02	0	200	2.33	510	7.25E-06		
0:35	25	4	Ag	45	0	43.6/61.6	1170	107.2/75.8	7.52E+02	4.67E+04	4.38E+01	4.18E+02	0	210	2.3	510	9.15E-06		abort: out of time/wrong angle
0:35	26	11	Ag	0	0	43.6	1170	107.2	7.41E+02	9.99E+04	6.62E+01	6.62E+01	0	180				F: SEGR	failed on stress test

Appendix D

Notes:

1. In Figures D1a and D2a, drain currents were read from the Agilent 6035A System Power Supply which has a readout accuracy of 0.5% + 50mA (worst-case), with a tolerance of +/- 1.25mA. These plots should be interpreted with this limited accuracy and tolerance in mind.

Figure D1a. Strip Tape of DUT 15 showing SEGR from 1170 MeV Silver ions (run 16). Ig current limit set to 1mA; current flow out of the gate is defined as negative. The magnitude change in drain current from pre- to post-gate failure is not resolvable (see note above).
Bias: 180 Vds, -5 Vgs.

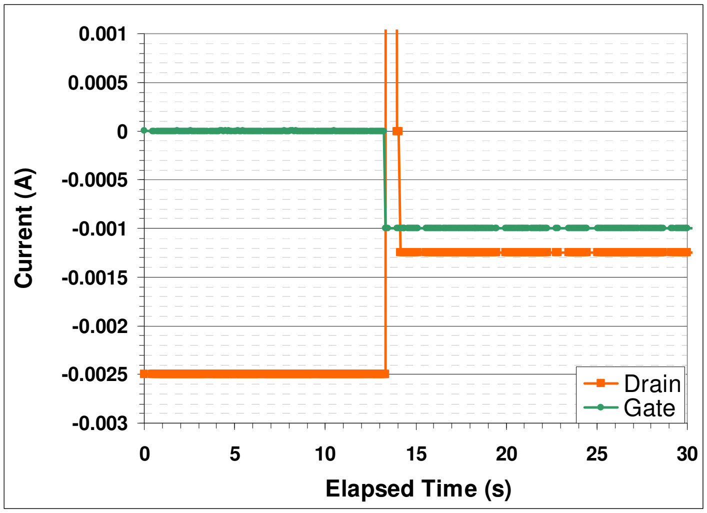


Figure D1b. Corresponding transient on source and drain nodes at time of break in Fig. D1a. Currents with magnitudes above 5A are clipped. Current flow out of the DUT source node is defined as positive Is; flow into the DUT drain node is defined as positive Id.

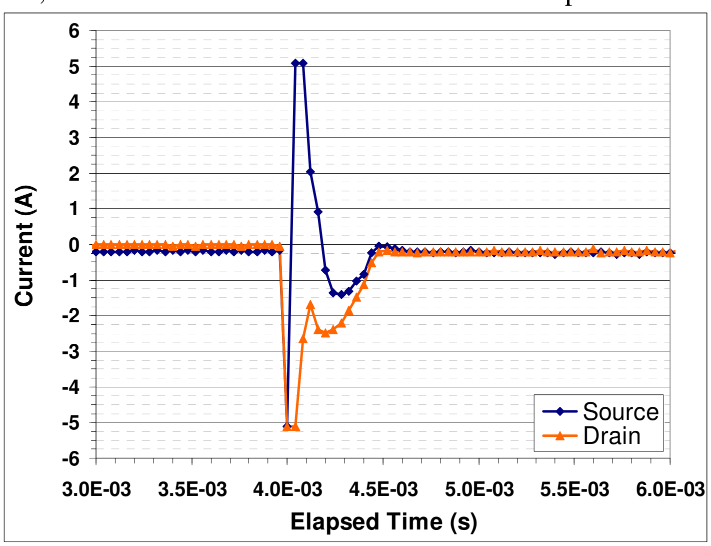


Figure D2a. Strip tape of DUT 208 gate and drain currents (run 23). Inset, higher-resolution plot reveals microbreak in gate just prior to increase in drain current. DUT 208 had been previously γ-irradiated to 4 krad (Si). Current limited to 1A and 1mA Ig during heavy-ion testing. Bias: 150 Vds, 0 Vgs.

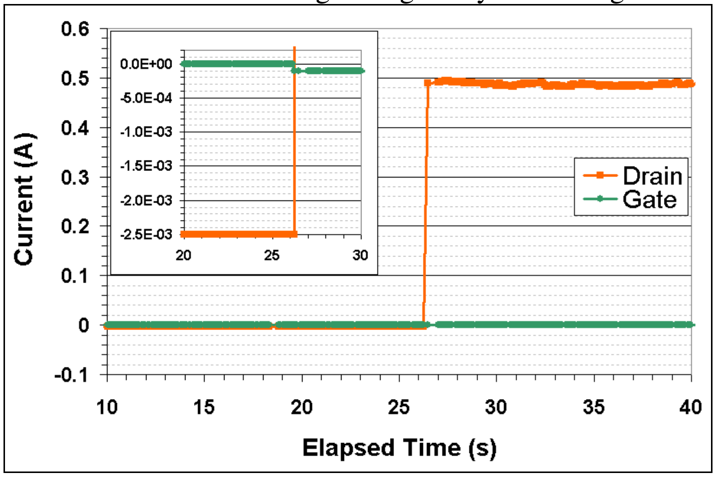


Figure D2b. Corresponding transient on source and drain nodes at time of break in Fig. D2a. Current flow out of the DUT source node is defined as positive Is; flow into the DUT drain node is defined as positive Id. Currents above 1A magnitude are clipped.

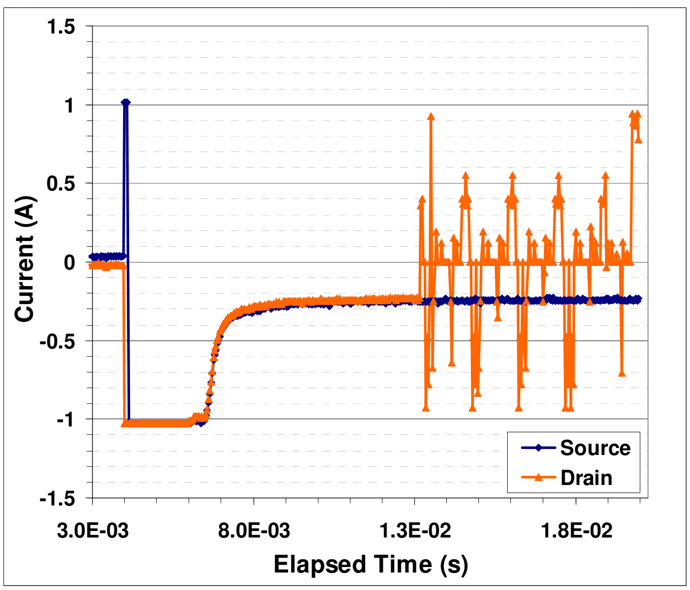


Figure D3. DUT 22 experienced SEB while irradiated at a 45° tilt with 953 MeV Krypton ions (run 8). Ions have greater projection along the gate interdigitation at this angle. Bias: 310 Vds, 0 Vgs.

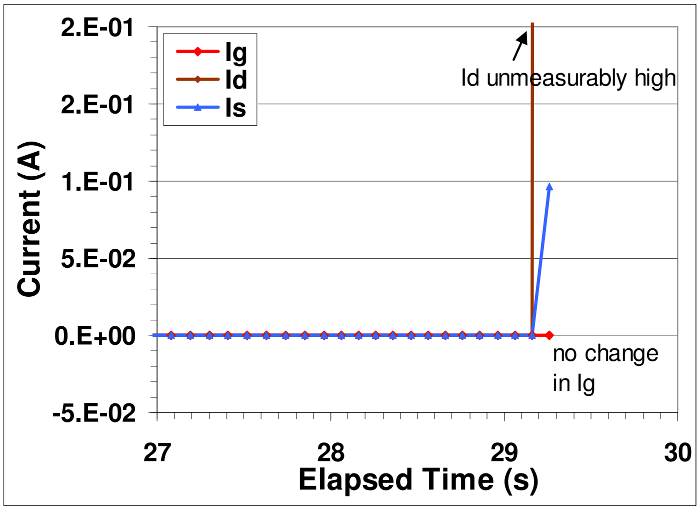
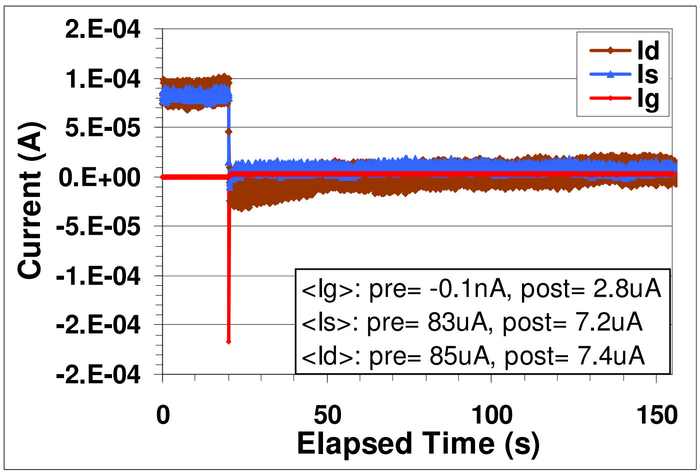


Figure D4. Microbreak in gate of DUT 35 under 953 MeV Kr irradiation at 45° roll angle (run 14). Ions have greater projection across the gate interdigitation at this angle. Average pre- and post-microbreak currents are given in the plot. Note that the elevated Ids prior to the gate microbreak is due to the accumulated dose from the previous runs. Bias: 310 Vds, 0 Vgs.



ADDENDUM

Heavy-ion testing was conducted on 4 additional APT50M38PLL devices from the same procurement and same lot date code as the devices previously tested. These tests were performed on December 16, 2008 and March 6, 2009 in order to further explore the influence of heavy-ion dose on the threshold bias required for SEGR.

Test Conditions:

All tests were conducted at Texas A&M University Cyclotron Single Event Effects Test Facility using the same silver ion beam conditions as in the original test report: 1170 MeV silver ions at 5 x 10^3 particles/cm^2/s flux and 1 x 10^5 particles/cm^2 maximum fluence level. The tests were performed at normal incidence using the test setup and equipment shown in Figure 2 and described in section IV of the original test report. Test personnel for the December 16, 2008 testing included Jean-Marie Lauenstein (NASA/GSFC), Hak Kim (MEI Technologies), and Mark Friendlich (MEI Technologies). Tests on March 6, 2009 were conducted by Jean-Marie Lauenstein and Anthony Phan (MEI Technologies). Table Add.1. lists the pre-test electrical characterization measurements for the test devices.

Test Results:

Two devices were irradiated with 1170 MeV silver ions while biased in the off-state at 0 Vgs and 126 Vds (safely below the bias for destructive failure). For the first device (serial number 10), a total dose of 1.9 krad (Si) was delivered over a span of 9 beam runs in between which the threshold gate voltage (Vth) was measured and recorded (see Table Add.2). This device's intial Vth of 4.05V degraded to 1.75V. The device was then immediately tested for SEGR in the standard way by incrementing the Vds while holding the gate at 0Vgs. As can be seen in Table Add.2, this device experienced SEGR during the gate stress test after irradiation at 180 Vds. After its last passing Vds of 170V, its Vth measured 1.70V. The second device (serial number 12) received a total dose of 1.8 krad (Si) in a single beam run while biased at 126Vds and 0Vgs. Its initial Vth of 3.71V degraded to 1.59V. SEGR testing was then performed, yielding a last pass/first fail Vds of 150V/160V. The Vth after the last passing Vds was measured at 1.60V (see Table Add.2).

In light of the small sample size of three pristine devices originally tested in September and November 2008 (recall one of these three devices was tested only at its failing Vds of 180V), two additional pristine devices were tested in March, 2009. As expected, both devices experienced degradation of their gate Vth to below vendor specification after only 70 rad (Si) during SEGR testing (see Table Add.3). These devices both demonstrated a last pass/first fail Vds of 150V/160V.

Summary and Conclusions:

Figure Add.1 provides a summary of the SEGR test results as a function of heavy-ion dose for all devices tested at normal incidence. In this figure, the x-bars show the dose accumulated during actual SEGR testing. The filled markers show the results for the two devices which were dosed with 1170 MeV silver ions prior to SEGR testing. The dramatic degradation of gate threshold voltage after very small levels of accumulated heavy-ion dose is even more remarkable in light of the columnar recombination that occurs and is not accounted for in these dose numbers. The actual dose received would therefore be even less than that indicated.

Despite this significant degradation of gate threshold voltage after very small levels of accumulated heavy-ion dose, the data suggest that this degradation does not influence the threshold bias required for SEGR. One pristine device (serial number 11, Table C2) was irradiated only at 180Vds (and 0Vgs) in order to ensure that the bias for failure was not artificially lowered due to dose accumulated during SEGR testing. Two additional devices were pre-dosed with silver ions at a Vds well below the

SEGR threshold bias until the gate threshold voltage had degraded to less than half the original value (well below vendor specification). No effect was found on the minimum Vds required for SEGR. The results of this test report may therefore be applicable to the relatively low heavy-ion dose conditions of typical space missions; however, further studies would be needed to increase the sample size and to explore the possibility of competing effects of heavy-ion dose versus gate threshold voltage degradation-induced device turn-on since these tests were performed at the nominal 0Vgs off-state bias.

Table Add.I: Pretest Characterization of DUTs. Note that the maximum measurable BVdss is 511V due to equipment limitation; for devices tested on December 16, 2008, Idss is not indicated due to an error in measurements.

Part SN	Vth	BVdss	Idss	Igss +/-
	(Volts)	(Volts)	(uA)	(nA)
10	4.05	511		32.9/22.6
12	3.71	511		24.7/40.6
234	3.81	511	63.2	18.5/39.4
146	3.78	511	4.9	21.5/43.0

Table Add.2: Test data from 16 December 2008. Beam diameter = 2 inches; 5cm airgap.

Time	Run	S/N	Ion	Tilt	Roll	LET	Energy	Range	Ave. Flux	Fluence	Dose	Cum. Dose	VGS	VDS	Vth	BVdss	Pass/ Fail	comments
	#			deg	deg	MeV.cm2/mg	MeV	µm	#/cm2/sec	#/cm2	rad (Si)		V	V	V	V		
2:38	11	10	Ag	0	0	43.6	1170	107.2	5.14E+03	3.02E+05	2.11E+02	2.11E+02	0	126	2.73			
2:41	12	10	Ag	0	0	43.6	1170	107.2	1.95E+03	2.05E+03	1.43E+00	2.12E+02	0	126				abort: recording out of synch
2:42	13	10	Ag	0	0	43.6	1170	107.2	5.05E+03	2.01E+05	1.40E+02	3.52E+02	0	126	2.68			
2:46	14	10	Ag	0	0	43.6	1170	107.2	4.83E+03	3.01E+05	2.10E+02	5.62E+02	0	126	2.15			
3:03	15	10	Ag	0	0	43.6	1170	107.2	5.03E+03	1.22E+05	8.52E+01	6.47E+02	0	126	2.09			
3:05	16	10	Ag	0	0	43.6	1170	107.2	4.88E+03	1.99E+05	1.39E+02	7.86E+02	0	126	2.02			
3:09	17	10	Ag	0	0	43.6	1170	107.2	4.74E+03	3.00E+05	2.10E+02	9.96E+02	0	126	1.95	511		
3:17	18	10	Ag	0	0	43.6	1170	107.2	4.83E+03	3.98E+05	2.78E+02	1.27E+03	0	126	1.89			
3:21	19	10	Ag	0	0	43.6	1170	107.2	4.59E+03	8.95E+05	6.25E+02	1.90E+03	0	126	1.75	511		
3:29	20	10	Ag	0	0	43.6	1170	107.2	4.52E+03	9.95E+04	6.95E+01	1.97E+03	0	140	1.75			
3:32	21	10	Ag	0	0	43.6	1170	107.2	4.73E+03	1.02E+05	7.13E-01	1.97E+03	0	150	1.74			
3:34	22	10	Ag	0	0	43.6	1170	107.2	4.63E+03	9.94E+04	6.94E+01	2.04E+03	0	160	1.72			
3:36	23	10	Ag	0	0	43.6	1170	107.2	4.48E+03	9.94E+04	6.94E+01	2.11E+03	0	170	1.70	511		
3:40	24	10	Ag	0	0	43.6	1170	107.2	4.68E+03	1.02E+05	7.09E+01	2.18E+03	0	180			Fail	broke on stress test
3:53	25	12	Ag	0	0	43.6	1170	107.2	1.02E+05	2.54E+06	1.77E+03	1.77E+03	0	126	1.59	511		Dosing
3:57	26	12	Ag	0	0	43.6	1170	107.2	5.02E+03	9.87E+04	6.89E+01	1.84E+03	0	150	1.60			start SEGR testing
3:59	27	12	Ag	0	0	43.6	1170	107.2	4.91E+03	9.77E+04	6.82E+01	1.91E+03	0	160			Fail	broke on stress test

Table Add.3: Test data from 6 March 2009. Beam diameter = 2 inches; 5cm airgap.

Time	Run	S/N	Ion	Tilt	Roll	LET	Energy	Range	Ave. Flux	Fluence	Dose	Cum. Dose	VGS	VDS	Vth	BVdss	Idss	Pass/ Fail	comments
	#			deg	deg	MeV.cm2/mg	MeV	µm	#/cm2/sec	#/cm2	rad (Si)		V	V	V	V	µA		
14:22	36	234	Ag	0	0	43.6	1170	107.2	3.72E+03	1.01E+05	7.07E+01	7.07E+01	0	130	2.89	500	63.7		
14:26	37	234	Ag	0	0	43.6	1170	107.2	4.00E+03	9.83E+04	6.86E+01	1.39E+02	0	140	2.61	500	65.1		
14:30	38	234	Ag	0	0	43.6	1170	107.2	3.76E+03	9.89E+04	6.91E+01	2.08E+02	0	150	2.44	500	66.0		
14:40	39	234	Ag	0	0	43.6	1170	107.2	2.69E+03	9.99E+04	6.97E+01	2.78E+02	0	160				Fail	Broke on stress test
16:09	40	146	Ag	0	0	43.6	1170	107.2	3.75E+03	9.90E+04	6.91E+01	6.91E+01	0	140	2.73		8.5		
16:12	41	146	Ag	0	0	43.6	1170	107.2	3.62E+03	9.99E+04	6.97E+01	1.39E+02	0	150	2.43		12.6		
16:14	42	146	Ag	0	0	43.6	1170	107.2	3.53E+03	1.01E+05	7.05E+01	2.09E+02	0	160				Fail	Broke on stress test

Figure Add.1: Mean drain-source threshold voltage for SEGR as a function of accumulated heavy-ion dose. Y-bars show measurement error; x-bars indicate dose accumulated during SEGR testing. Open markers indicate initially pristine-device data; filled markers show SEGR test results for the devices initially exposed to 1170 MeV silver ions while biased at 0Vgs, 126Vds. Tests were conducted with a normally-incident beam and with 0 Vgs.